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System identification in Priming of Pop-Out

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ABSTRACT

Inter-trial repetitions of a target's features in a visual search task reduce the time needed to find the target. Here I examine these sequential dependencies in the Priming of Pop-Out task (PoP) by means of system identification techniques. The results are as follows. Response time facilitation due to repetition of the target's features increases linearly with difficulty in segmenting the target from the distracters. However, z-scoring the reaction times normalizes responses by equating facilitation across levels of difficulty. Memory kernels, representing the influence of the current trial on any future trial, can then be calculated from data normalized and averaged across conditions and observers. The average target-defining feature kernel and the target position kernel are well fit by a sum of two exponentials model, comprised of a high-gain, fast-decay component and a low-gain, slow-decay component. In contrast, the average response-defining feature kernel is well fit by a single exponential model with very low-gain and decay similar to the slow component of the target-defining feature kernel. Analysis of single participant's data reveals that a fast-decay component is often also present for the response-defining feature, but can be either facilitatory or inhibitory and thus tends to cancel out in pooled data. Overall, the results are similar to integration functions of reward history recently observed in primates during frequency-matching experiments. I speculate that sequential dependencies in PoP result from learning mechanisms that bias the attentional weighting of certain aspects of the stimulus in an effort to minimize a prediction error signal.

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1. Introduction

Inter-trial repetitions of a target's features in a visual search task reduce the time needed to find the target relative to the series' average, whereas alternations tend to increase it (Maljkovic & Nakayama, 1994). By adopting a form of reverse correlation analysis of reaction times and stimulus sequences, Maljkovic and Nakayama computed kernel functions for such sequential effects in the Priming of Pop-Out task (PoP), documenting the influence that a current trial exerts on future trials. Subsequent studies (Kristjansson, 2008; Maljkovic & Martini, 2005; Maljkovic & Nakayama, 1996, 2000) have mapped a variety of conditions that alter the characteristics of such kernels in varying degrees. However, a quantitative modeling of such dependencies has yet to be attempted and there appears to be no general consensus on the interpretation of the nature and the functional significance of the sequential dependencies observed in PoP. Proceeding from these observations, the goal of the present study is twofold: firstly, to provide a quantitative characterization of PoP kernels and secondly to propose a new theoretical account of their nature and functional significance. To such effect, I chose to study the effect of stimulus contrast on PoP. Varying stimulus contrast is a means to manipu-

late difficulty in segmenting the target from the distracters and here I show that the magnitude of sequential dependencies depends on difficulty. As such, manipulations of contrast provide a way of exploring the dynamic range of the sequential effects.

The plan of the paper is as follows. I start by demonstrating a way to normalize responses across conditions and across observers, showing that z-scoring the reaction times removes the effect of task difficulty on the magnitude of response facilitation. I then identify the system in two steps: firstly, I compute kernels non-parametrically from normalized data by cross-correlation; secondly, I fit a parametric model to the recovered kernels averaged across observers. I then conduct similar analyses on data from single observers and discuss individual differences. Finally, I discuss functional implications of the modeling.

2. Methods

2.1. Participants

Forty-seven undergraduate students participated in the experiment for course credit. Three additional experienced observers were also tested: observers PM (the Author) and VM have several years of practice in the task and were aware of the purpose of the experiment, whereas LB is an experienced psychophysical

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observer, but was unaware of the scope of the experiment she was running.

2.2. Stimuli

Three diamonds ($1.0^\circ \times 1.0^\circ$), each with a cutoff ($.14^\circ$) on the left or right side, were presented on an imaginary ellipse ($10^\circ \times 8^\circ$) and spaced equidistantly, such that they fell on three of 12 possible clock positions (see Fig. 1). All spatial configurations were covered uniformly across trials by random choice. The color of each diamond was either a grayscale increment or a decrement over a 47 cd/m^2 mid-gray background. Increments or decrements of 5%, 10% and 40% were used for naïve participants and two additional steps of 20% and 80% for the experienced observers. The target diamond was a different color than the two remaining distracters. Each display always had a left and a right side cut distracter, while the target cut was chosen randomly on each trial. The displays were presented on a CRT monitor at a refresh rate of 120 Hz, with a fixation point always present at the center.

2.3. Procedure

On each trial, participants selected the odd-colored diamond and pressed as quickly as possible a key on the computer's keyboard (USB interface) with the hand corresponding to the side of the target's cut. Stimuli stayed on-screen until a response was entered. An inter-trial interval followed, with duration chosen randomly from a uniform distribution between 600 and 1100 ms. Response times were collected during uninterrupted series of 500 trials. Each naïve participant completed three series of responses separated by brief interruptions, one for each contrast level in randomized order. The three experienced observers completed several sessions of testing across different days. Target color (bright or dark), side of cut (left or right) and position (one of 12 clock locations) alternated randomly, independently and with equal probabilities across trials. As such, each sequence is a sample of uncorrelated noise.

2.4. Data analysis

The aim of this study is to recover the best linear predictor of the response times to a sequence of stimulus features in the search task. When the input time series is uncorrelated noise this can be achieved conveniently by cross-correlation (Marmarelis & Marmarelis, 1978). The recovered predictor is a first-order kernel that when convolved with the input sequence reproduces the response time series up to an error. The residual error may still contain dynamics of higher order that are ignored in the present analysis. First-order kernels for the target-selecting feature (color), for the target's position and for the response-selecting feature (cut-off side) were computed from the reaction time series. For each participant, each individual reaction time series was first de-trended up to second order. Separate sub-series were then formed, two

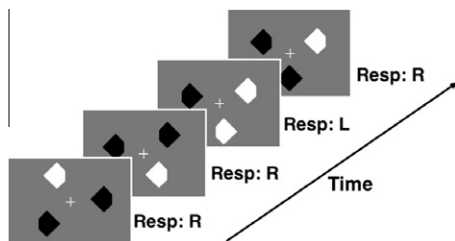


Fig. 1. Example of stimuli used in the experiment. Participants responded by pressing a key with the hand corresponding to the side of the cut in the odd-colored diamond.

comprising only reaction times to bright or dark targets, two for left or right responses and twelve for the target's positions. Each reaction time was then z-scored (mean subtracted and divided by the standard deviation) and empty cells were assigned the value zero. Corresponding [0, 1] binary stimulus sub-series were also formed, assigning the value 1 to trials containing the feature, response or position of interest. Kernels were then recovered by cross-correlating the reaction time sub-series with the corresponding stimulus sub-series and by scaling the result by the inverse of the stimulus series' power. Justification and a model for such computation was given in Maljkovic and Martini (2005). Further computational details may be found in (Marmarelis & Berger, 2005). For each individual observer, the pairs of kernels for color (bright and dark) and response (left and right) and the 12 position kernels were averaged, and finally the resulting average kernels were averaged again across observers. Following this initial nonparametric analysis, a parametric model was fitted by non-linear regression to each recovered kernel, obtaining estimates of model parameters of interest.

3. Results

3.1. Contrast dependence and kernel normalization

Finding the pop-out target is more difficult at low than at high contrast, as evidenced by the fact that responses are slower on average and more variable the lower the contrast (mean and SD, Fig. 2).

Kernels for the target-defining feature are also affected by contrast. The facilitatory effect of repeating the target-defining feature depends on difficulty, lag-1 facilitation being larger at low than at high contrast (lag-1, Fig. 2). Shown in Fig. 3 are target-defining feature kernels averaged across participants, for the three levels of contrast tested in the experiment. The diagrams represent the amount of facilitation (speeding up) of a response to a bright or dark target encountered in a future trial, elicited by a bright or dark target encountered in the current trial. A similar pattern is observed across contrast levels: facilitation is maximal in the immediately following trial (lag-1) and decays to average response time in about 10–15 trials. However, facilitation tends to decrease with increasing contrast, following a similar trend as the mean response time and the standard deviation.

The effect of contrast on all three statistics (mean, SD and sequential dependencies) is systematic, with regression slopes on the log-log-transformed data of Fig. 2 of -0.086 , but only marginally significant ($p < 0.1$).

The relationships between sequential effects, mean and standard deviation of response times are further examined in the scatterplots of Fig. 4. Individual dots in each graph represent a summary statistic calculated on a block of responses at a single contrast level from a single participant. Replicating a well-known

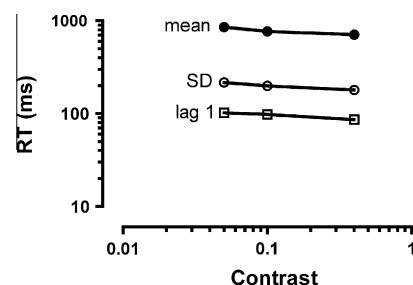


Fig. 2. Summary statistics for reaction times at different contrasts. Mean and standard deviation of reaction times and lag-1 facilitation for repetition of the selection-defining feature decrease with increasing contrast. Data are averages across all observers.

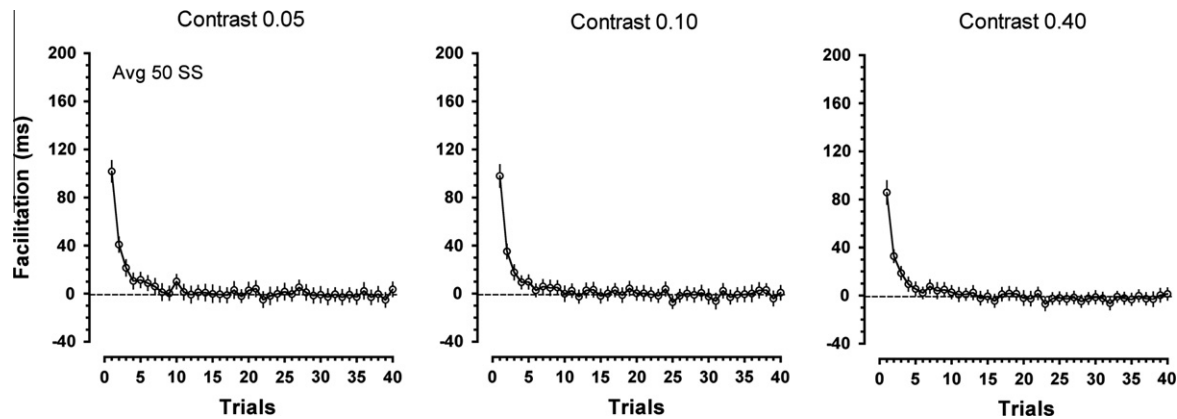


Fig. 3. Average selection-defining feature kernels for the three contrast levels used in the study. All kernels are heavy-tailed facilitation functions, with an initial fast decay followed by a slow decay to average response time in about 10–15 trials. Notice the progressive attenuation with increasing contrast, evident particularly a lag-1. Errors are 95% C.I.

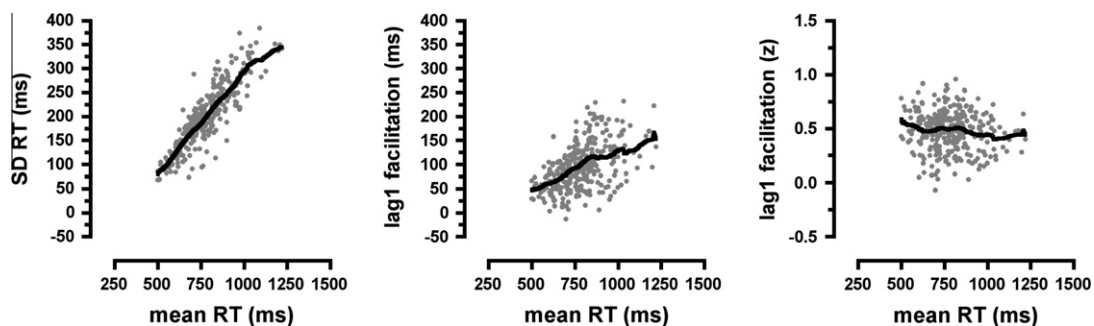


Fig. 4. Scatterplots of data pooled across participants and contrast levels. Solid lines through the data are LOWESS splines. On the left, the standard deviation of the response times for each contrast level and each participant is plotted as a function of the mean response time; the correlation between standard deviation and mean RT is very high ($r = 0.88$, $p < 0.0001$). Middle, lag-1 facilitation is correlated with the mean ($r = 0.5$, $p < 0.0001$). Right, lag-1 facilitation calculated on z-scored data does not correlate with the mean ($r = -0.09$, $p > 0.10$).

finding (Wagenmakers & Brown, 2007), the standard deviation of the response times (Fig. 4, left panel) is linearly and very highly correlated with mean reaction time ($r = 0.88$, $p < 0.0001$). As expected from its dependence on contrast, also lag-1 facilitation (Fig. 4, middle panel) correlates significantly with mean reaction time ($r = 0.5$, $p < 0.0001$). However, z-scoring each reaction time series normalizes responses (Fig. 4, right panel), such that facilitation no longer correlates with the mean ($r = -0.09$, $p > 0.1$).

In summary, facilitation appears to increase with difficulty in segmenting the target from the distracters, but such effect is canceled by taking into account corresponding increases in variance. This may be an uninteresting result from a theoretical perspective, suggesting that whatever mechanism is responsible for increasing the variance of reaction times proportionally to the mean also increases proportionally the magnitude of sequential dependencies. However, it is of practical value inasmuch as it suggests a useful method of normalization.

3.2. Average kernels

The effectiveness of z-scoring as a normalization procedure justifies pooling the data across all contrast levels and participants, thus allowing for the computation of the average kernels shown in Fig. 5. The recovered kernels were modeled as the sum of two exponential functions:

$$y = w_1 \exp\left(-\frac{x}{\tau_1}\right) + w_2 \exp\left(-\frac{x}{\tau_2}\right) \quad (1)$$

Eq. (1) was fitted to the data by non-linear regression.

For the target-defining feature (Fig. 5, left) and the target position (Fig. 5, right), the obtained best fitting parameters indicate a

fast-decay component with a time constant less than one trial (selection feature: $w_1 = 1.33 \pm 0.14$, $\tau_1 = 0.79 \pm 0.1$; target position: $w_1 = 0.52 \pm 0.4$, $\tau_1 = 0.65 \pm 0.37$) and a slow-decay component with a time constant of about five trials and a much smaller gain (selection feature: $w_2 = 0.14 \pm 0.14$, $\tau_2 = 4.2 \pm 1.0$; target position: $w_2 = 0.09 \pm 0.03$, $\tau_2 = 6.3 \pm 2.0$). The best fitting model for the response-defining feature kernel is instead a single exponential function, with decay constant similar to the slow-decay component of the selection-defining feature kernel, but even lower gain ($w_2 = 0.05 \pm 0.01$, $\tau_2 = 4.6 \pm 1.15$).

3.3. Single participant kernels

Kernel analyses for color and response were also carried out on the data obtained from three experienced observers, shown in Fig. 6. Individual kernels for the selection-defining feature are broadly similar to the pooled data. However, the kernels for the response-defining feature are very heterogeneous and well modeled by a sum of two exponential functions, unlike the pooled data. Model's parameters are reported in Table 1. Characteristically, the fast-decay component of the model has positive or negative gain in different observers. In addition, the slow component appears to extend to longer lags in practiced versus naïve observers.

4. Discussion

4.1. Relation to previous studies of PoP

The original study of Maljkovic and Nakayama (1994) reported kernels for selection-defining features computed on data from a small number of individual observers, including VM, the first

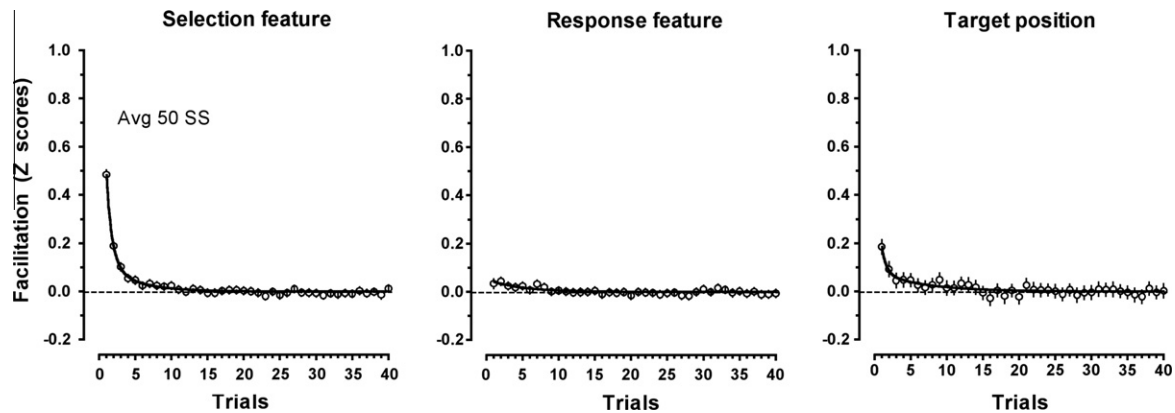


Fig. 5. Kernels for the selection-defining feature (left), the response-defining feature (middle) and target position (right) computed on z-scored data and averaged across contrast levels and participants. Errors are 95% C.I. The solid line through the data is a sum of two exponentials model for the selection feature and target position and single exponential for the response feature.

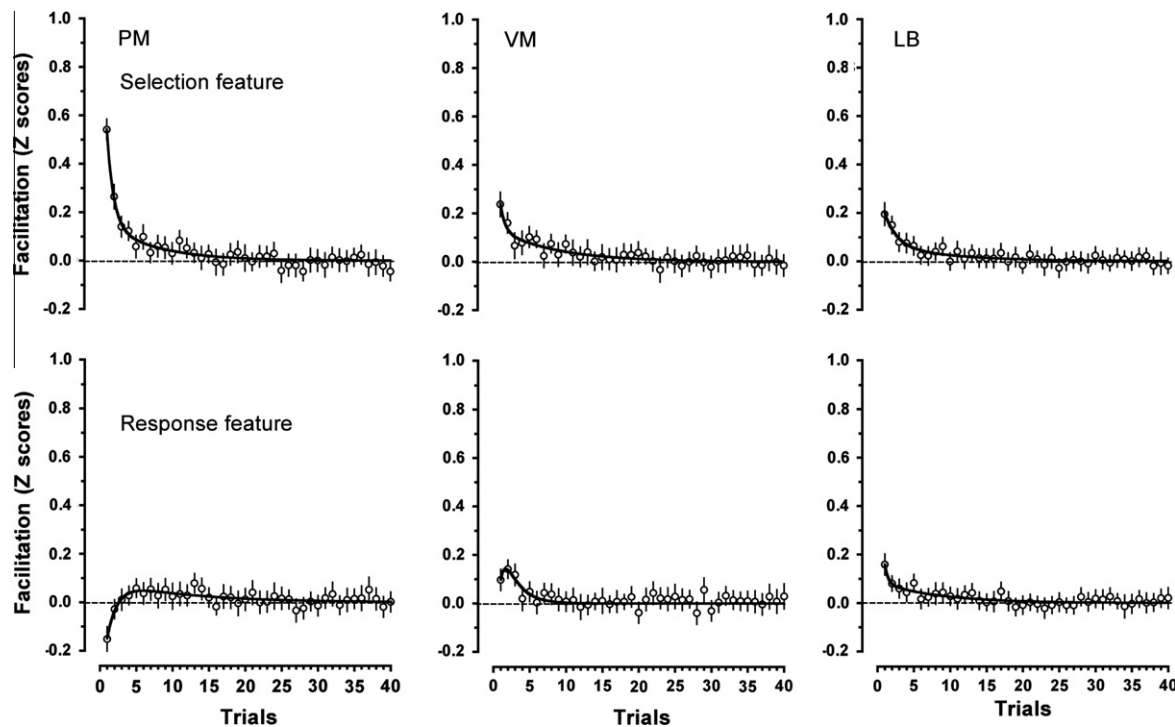


Fig. 6. Kernels for the selection-defining feature and the response-defining feature computed from the z-scored data of three individual observers. Solid lines are sum of exponentials models and errors are 95% C.I.

Table 1
Model's parameters for single observers.

Observer	Feature	w_1	τ_1	w_2	τ_2
PM	Color	1.2 ± 0.25	0.9 ± 0.2	0.17 ± 0.06	6.9 ± 1.9
	Response	-0.48 ± 0.08	1.42 ± 0.4	0.1 ± 0.04	10.7 ± 3.8
VM	Color	0.43 ± 0.31	0.78 ± 0.5	0.14 ± 0.03	8.4 ± 1.9
	Response	-1.0 ± 0.6	0.64 ± 0.4	0.5 ± 0.4	1.9 ± 0.7
LB	Color	0.24 ± 0.05	1.7 ± 0.77	0.07 ± 0.05	9.5 ± 4.4
	Response	0.66 ± 1.4	0.47 ± 0.5	0.09 ± 0.02	8.1 ± 2.2

Author of that study. There is remarkable agreement between the selection-defining kernels of observer VM computed in the original and the present study after a 15 years period (see Fig. 7). This is just one example of a general observation that selection-defining feature kernels appear stable and homogenous across different

display conditions, temporal delays and observers, particularly when normalization measures, such as z-scoring, are applied.

In contrast, Maljkovic and Nakayama (1994) reported no convincing evidence for the existence of a response-defining feature kernel, an observation later reproduced by Maljkovic and Martini (2005). This issue was reexamined by Goolsby and Suzuki (2001): they documented a small, but reliable response-defining feature kernel in pooled data and the present study agrees with their finding. Reliable quantification of response-defining feature kernels is complicated by the small effect size and low signal/noise ratios, by the presence of stimulus–response compatibility effects (note that responses in Maljkovic & Nakayama (1994) were unimanual and therefore partially S–R incompatible, whereas in the present study and in Goolsby and Suzuki (2001)) they were bimanual and S–R compatible) and by large heterogeneities found across observers, particularly at lags shorter than three. These

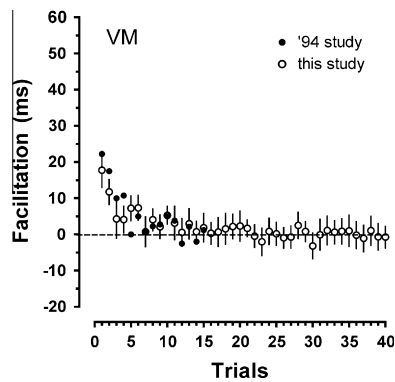


Fig. 7. Selection-defining feature kernels for participant VM. Empty symbols are data from this study, solid symbols reproduce data from Fig. 9 of Maljkovic and Nakayama (1994).

complications have affected past, and will continue to affect future investigations of the response-defining feature kernel.

4.2. Parametric modeling of kernels

Extant studies of PoP have not attempted to quantify the recovered kernels by explicit modeling. The only possible exception is the study of Maljkovic and Martini (2005), limited to a single observer, where the selection-defining feature kernel was modeled as a single exponential function. Except in the case of the response-defining feature kernel for the average data, a single exponential function is not an adequate model for the present data: the best-fit solution of such model tends to under-fit data at short and long lags and to over-fit them at intermediate lags. The pattern observed in the data, i.e. an initial fast decay followed by a fat tail, is more consistent with a power type relationship. The model proposed here, i.e. the sum of two exponentials, approximates a power type function, but retains the advantage of having a finite memory. Whether the two exponential components of the model reflect two real, independent mechanisms can at present only be a matter of speculation. It is possible that the initial fast-decay component is, at least in part, contaminated by consciously explicit adjustments on the part of the observer. For example, Maljkovic and Nakayama (2000) reported explicit memory for the features of up to two trials in the past. Consistent with the idea of a separable fast-decay component is the observation that the kernel for the response-defining feature is maximally heterogeneous across observers in the initial ~ 3 lags, varying between inhibition and facilitation, whereas later lags tend to uniformity by showing always a consistent, albeit small, facilitatory tail. Note also that the time constant of the slow component is significantly longer in practiced than naïve observers, suggesting some plasticity due to training. It remains for future studies to explore the possibility of selectively manipulating performance in different lags' ranges, thereby establishing whether the proposed kernel's fractionation reflects true separate influences or is simply a convenient modeling exercise.

4.3. Similarities between PoP and other sequential dependencies

The study of sequential dependencies in behavioral data has a long history. Looking beyond the PoP task, sequentially dependent behavior has been observed in virtually every choice task studied, including production of random data (Goodfellow, 1938; Hagelbarger, 1956; Skinner, 1942), detection of liminal signals (Senders & Sowards, 1952; Verplanck, Collier, & Cotton, 1952), speeded choice among alternatives (Bertelson, 1965; Laming, 1969), magnitude estimation (DeCarlo & Cross, 1990), categorization (Stewart,

Brown, & Chater, 2002), sensori-motor adaptation (Baddeley, Ingram, & Miall, 2003) and reward-contingent choice (Corrado, Sugrue, Seung, & Newsome, 2005; Hunter & Davison, 1985; Lau & Glimcher, 2005). The list is certainly not exhaustive, but in all these instances the observed pattern of sequential dependencies can be reduced to two common types, classically known as “contrast” and “assimilation” (Treisman & Faulkner, 1984). Contrast is a repulsive influence and reflects a tendency to alternate, whereas assimilation indicates positive correlation and reflects a tendency to persist. PoP kernels are mostly of the assimilation type, but the inhibitory component sometimes present in the response-defining feature kernel is clearly an example of a contrastive influence.

Two recent investigations of the mechanisms for integration of rewards (Corrado et al., 2005; Lau & Glimcher, 2005) come the closest, in terms of task demands and analytical methods, to the study of kernels in PoP. The similarity between the kernels retrieved in those studies and the present study is intriguing: both reward studies reported heavy-tailed kernels for reward and heterogeneous kernels for response. Is this simply a fortuitous similarity?

4.4. Prediction and learning in PoP

Ideas from behavior, neuroscience and machine learning have been brought together into a coherent explanatory framework for kernels observed in reward-contingent behavior, understood as the result of reinforcement learning (Sugrue, Corrado, & Newsome, 2005; Sutton & Barto, 1998). Central to this type of theories is the concept of temporal difference learning, where choices are driven by a value function that is iteratively updated on every trial. Learning proceeds by minimizing a prediction error, adding to the value function at every trial a weighted difference between the reward received and the previously expected value. The prediction error acts as a teaching signal, such that learning can proceed unsupervised.

In contrast, sequential dependencies in visual search have been interpreted as a form of implicit short-term memory that biases attentional weights for certain aspects of the stimulus (Maljkovic & Nakayama, 2000). Note, however, that the characterization of the kernel as a memory is simply a restatement of the phenomenon. Furthermore, the notion that repetition of a stimulus' feature increases attention toward that feature leaves unanswered the question as to why it should be so: why is not attention reduced, rather than increased by repetition?

I suggest that a coherent framework to explain kernels in PoP can be articulated by considering task goals and ecological contingencies. Finding a target among distractors may benefit from learning about the regularities in the distribution of the items. By exploiting such regularities the observer can anticipate the most likely stimulus configuration in the upcoming trial, thus speeding up responses. The assumption here is that such regularities do exist, but this is not often the case in laboratory tasks: in the classic PoP task, for example, all stimulus features are equiprobable and alternate randomly. Yet, in nature completely random time series are the exception rather than the norm, as attested by the observation of widespread $1/f$ -type spectra (Hurst, Black, & Simaika, 1965). Not only are most natural time series temporally correlated, but also the spatial distribution of resources is often patchy (Taylor, Woivod, & Perry, 1978), such that exploration of the environment also results in sequences of correlated encounters. As such, prediction is clearly attainable in ecological settings and predictive tendencies are likely to be the evolved operational default of behaving organisms.

These considerations suggest that kernels in PoP may reflect a similar prediction algorithm as that postulated to exist for reward. The suggestion here is that value functions, computed by means of

unsupervised learning through a prediction error signal, may drive the attentional weight given to stimulus features and thus affect the speed of response. In classic temporal difference learning algorithms (Sutton & Barto, 1998), iterative value updating by a prediction error signal leads to exponentially discounted kernels. The observation that PoP kernels may have two exponential components suggests that the values of alternatives are computed by at least two mechanisms with different learning rates, one greedy and one slow. Similar suggestions have been made in the reward and decision-making literature (McClure, Ericson, Laibson, Loewenstein, & Cohen, 2007; Rustichini, 2008). Bringing the sequential effects observed in PoP under the general umbrella of reinforcement learning and decision-making highlights the commonalities between fluctuations of attentional weights and of motivational salience (Maunsell, 2004) and suggests testable predictions about mechanisms and neural structures.

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